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by James W. Blue and Theodore E. Fessler
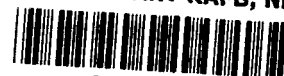
Lewis Research Center
Cleveland, Ohio

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A fast-neutron irradiation of both equilibrium and normal liquid hydrogen was performed and analyzed for evidence of conversion. The data indicated that radiation-induced ortho- to para-hydrogen conversion occurs in liquid normal hydrogen but is less than 5×10^{-3} mole fraction for an integrated neutron flux of 5×10^{13} neutrons per square centimeter. A pronounced effect of irradiation was the destruction of superheat in the liquid-hydrogen bath surrounding the test samples. This effect caused a decrease in the temperature of the bath and thereby complicated the data analysis.

INTRODUCTION

The anticipated use of hydrogen as the propellant for nuclear rockets has prompted several studies of the problems arising from neutron and gamma-ray irradiation of liquid hydrogen. References 1 and 2, for example, consider the problem of how to calculate the energy deposited in liquid hydrogen from a given radiation field. In these studies, the observed radiation is assumed to appear as a heating load on the propellant; that is, the chain of events (on the microscopic level) which ultimately results in the appearance of thermal energy is considered unimportant to the final results. It is pointed out, however, that all the absorbed energy need not appear immediately as heat but can be stored in various excited species of atoms and molecules for times appreciable even in the macroscopic view.

In the microscopic view, the primary interaction is that fast neutrons produce recoil protons and gamma-radiation produces Compton scattered electrons when incident on a volume of liquid hydrogen. Reference 3 considers the possible reactions as these charged particles pass through liquid hydrogen and concludes that the species H_2^+, H_2^-,

H, H^+, and H^- will all be present. It furthermore concludes that a significant fraction of the kinetic energy of the primary charged particles is temporarily stored during the production of these species and suggests that the lifetime of some of these species may be comparable to the propellant discharge time.

The present investigation was a search for the radiation-induced conversion of ortho- to para-hydrogen. Such conversion could be caused by the generation of these species of atoms and molecules. In the liquid state, the spontaneous conversion of hydrogen from the ortho form in which the proton spins are coalined to the para form in which the spins are oppositely alined proceeds slowly by the reaction

$$H_2^O + H_2^O \rightarrow H_2^O + H_2^p$$
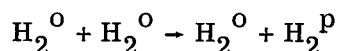
This reaction results from interactions between the weak dipole moments of neighboring ortho molecules and is not properly a chemical reaction. Chemical reactions of the type

$$H_2^O + X \rightleftharpoons X + H_2^p$$
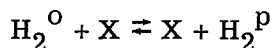
are conceivable, however, and, in fact, the reaction

$$H_2^O + H \rightleftharpoons H + H_2^p$$
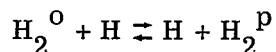
has received considerable attention (ref. 4). It is pointed out in reference 3 that this exchange reaction will not be important in liquid hydrogen even though radiation might provide a copious source of H atoms, because the fraction of molecules having kinetic energies greater than the activation energy for this reaction (0.3 eV) is much too small at 20° K. Whether or not one of the other species can enter into such an exchange reaction remains to be determined.

APPARATUS AND METHOD OF MEASUREMENT

Vapor-Pressure Apparatus

The design of the apparatus used in this experiment was based upon the fact that the vapor pressure of liquid hydrogen at a given temperature is a function of its ortho-para composition. In particular, at the normal boiling point of para-hydrogen (20.27^O K), normal liquid hydrogen (25 percent para, 75 percent ortho) displays a vapor pressure 26.1 millimeters of mercury (mm Hg) below that of the para form. Through comparison of the vapor pressures of two samples of liquid hydrogen held at the same temperature

it is therefore possible to infer changes in their relative ortho-para compositions or actually to determine the composition of one of them if the other is known. This method does not require that hydrogen be removed from either sample in order to make a composition determination. It thus has two distinct advantages over the gas conductivity method (ref. 4, p. 22): (1) An unlimited number of determinations may be made on one liquid sample, and (2) changes in sample composition due to fractionation are avoided.

Figure 1 is a diagram of the apparatus used to contain the liquid-hydrogen samples and to measure their vapor pressures. This system consists, simply, of a Dewar of liquid para-hydrogen that serves as a low-temperature reservoir for the two small sample bulbs immersed in it. This liquid-hydrogen Dewar is surrounded, except for the bottom 4 inches, by a liquid-nitrogen Dewar, which serves as a radiation shield. The bottom section of the inner Dewar was left unshielded so that the beryllium target could be brought up as close as possible to the sample bulbs. The sample bulbs were roughly cylindrical in shape; each one was approximately 3.5 centimeters long with a 1.2-centimeter inside diameter. The two sample bulbs were made of borosilicate glass (as was all the rest of the sample-containing system) and were fused together to provide a thermal connection between the bulbs and mechanical rigidity. The sample bulbs were connected to the external plumbing by 3-millimeter-inside-diameter capillary tubing. This external plumbing consisted of a three-leg manometer for measuring the vapor pressures against the atmosphere, two mercury filled "bubblers," which served as

Figure 1. - Liquid-hydrogen apparatus.

safety valves in case of inadvertant boiling off of the hydrogen samples, and stopcocks, which made possible evacuating the system and subsequent charging with the sample gases.

The sample bulbs were surrounded by two layers of fine mesh copper screen to minimize possible temperature fluctuations caused by heat leaking into the hydrogen bath through the unshielded portion of the inner Dewar. In addition, 0.006-centimeter-thick copper foil was used as a lining inside the unshielded section and as a radiation baffle above the bulbs.

Irradiation Facility

The Lewis Research Center 60-inch cyclotron facility was used in this experiment to
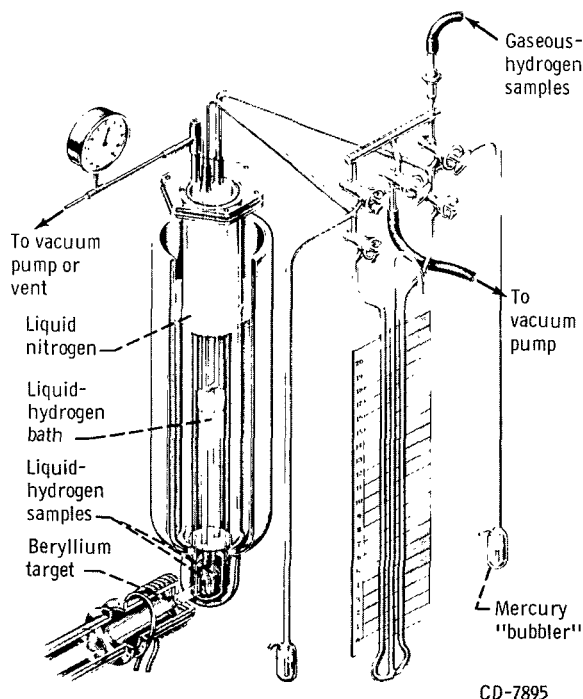
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provide a high flux of fast neutrons (about 10 MeV energy) throughout the two sample bulbs. The facility consists of a fixed-frequency 60-inch cyclotron located in a shielded vault and an adjacent shielded room designated the "beam room." The hydrogen-containing apparatus described in the preceding section was appropriately positioned in the beam room so that, when desired, a beam of 21 MeV deuterons from the cyclotron could be directed at a beryllium metal target located close to the outer wall of the un-shielded section of the hydrogen Dewar. The reaction of deuterons on beryllium has been observed (ref. 5) to produce fast neutrons and relatively little gamma radiation. The advantage is that fast neutrons deposit most of their energy in the liquid hydrogen, whereas gamma radiation deposits a much larger fraction of the energy in the glass walls.

The number of deuterons striking the target per second was determined by placing the beryllium target in a Faraday cup, which was connected to a current measuring electrometer. A circular aperture of slightly smaller diameter (16 mm) than that of the beryllium target was used to make certain that the measured beam current was due only to deuterons incident on the beryllium metal. This aperture was made in graphite and was located in the grounded section of the evacuated beam pipe. The Faraday cup was insulated from the grounded pipe by a rubber vacuum seal. De-ionized water supplied through long rubber hoses was used to remove the heat delivered by the deuteron beam (as much as 160 W). Leakage currents through these water lines were negligible in comparison with the measured beam currents.

In order to measure the liquid-hydrogen vapor pressures during irradiation, a television camera was set up to read the three-tube manometer remotely. The manometer fluid used was a brand of dinonylphthalate. This diffusion pump oil has a density of 0.97 gram per cubic centimeter at room temperature; this together with a long focal length lens on the television camera made possible accurate pressure measurements during neutron irradiation.

EXPERIMENTAL PROCEDURE

Since the purpose of this experiment was to measure the amount of ortho to para conversion due to neutron irradiation, minimizing spontaneous conversion was desirable. Among other contaminants, small amounts of oxygen in liquid hydrogen have long been known to increase the spontaneous conversion rate severalfold (cf. ref. 4, p. 79). Since the spontaneous conversion rate for clean hydrogen in glass systems has been measured (ref. 6), borosilicate glass was used for the sample bulbs, and they were carefully evacuated before being cooled to liquid-hydrogen temperatures.

Sample Bulb Filling

The first step in filling the sample bulbs was to fill the side arms of the measuring manometer (fig. 1) with the same kind of hydrogen later to be condensed in the sample bulbs. Filling was accomplished by evacuating all three arms to remove the bulk of the absorbed gases and then filling the two side arms by use of the side-arm stopcocks. When this operation was completed, the manometer stopcocks were closed and the sample bulbs and mercury bubblers evacuated by a diffusion pump to a residual pressure of 10^{-5} mm Hg. This pumping was continued during the hour or so required to cool the system to liquid-nitrogen temperature. When the apparatus was ready for introduction of the liquid hydrogen into the inner Dewar, the remaining stopcocks were closed to isolate the sample bulbs.

The sample bulbs were filled by pumping on the liquid-hydrogen bath and maintaining atmospheric pressure (limited by the mercury bubblers) in the sample bulb supply line. Para-hydrogen gas was obtained by dipping a small-diameter stainless-steel tube beneath the surface of liquid para-hydrogen in the supply Dewar. Normal hydrogen gas was obtained directly from a commercial high-pressure bottle. Unfortunately, the sample bulbs were not visible at the time of filling and therefore a procedure designed to fill the two bulbs equally was devised. This procedure involved pumping on the liquid bath until a depression in vapor pressure of approximately 180 mm Hg was achieved. This vapor pressure was then maintained by additional pumping as needed while gas at 1 atmosphere was delivered to the desired sample bulb. To obtain approximately equal volumes of liquid in the two bulbs, the condensation time was fixed at 5 minutes for each bulb. The bulbs were filled approximately half full by this method. The "para" bulb was filled first. After the "normal" bulb was filled, all stopcocks were closed for approximately 2 hours to allow time for the placement of the apparatus in the cyclotron facility beam room and for the hydrogen bath to warm back to the point where its vapor pressure again equalled local atmospheric pressure.

Pressure Measurements

By means of the television system, the three manometer tubes were measured to a precision of about 0.03 inch of oil (0.05 mm Hg). This precision was possible because of the long focal length television camera lens employed. Since the center leg of the manometer was open to the atmosphere, barometric pressure observations were necessary to obtain absolute vapor pressures from the side-leg readings. Barometric pressures were obtained from a mercury column barometer read to the nearest 0.01 inch and reduced to 0° C.

Neutron Irradiation

After the sample pressures were recorded for some $5\frac{1}{2}$ hours to establish the spontaneous conversion rate, the deuteron beam from the cyclotron was turned on briefly to aid in tuning the accelerator.

At approximately 9 hours after the hydrogen samples were condensed, the deuteron beam was again turned on. This time a beam current of approximately 7 microamperes was achieved. Beam currents were read from a current integrating device and occasionally recorded, as was the integrated charge. The irradiation proceeded without interruption for approximately 75 minutes.

The yield of fast neutrons from the interaction of 20 and 24 MeV deuterons incident on a thick beryllium target is given in reference 5. From this information a neutron flux in the sample is calculated to be about 2×10^9 neutrons per square centimeter per second for the 7-microampere current of 21 MeV deuterons. The resulting exposures were determined to be 6.8×10^{13} neutrons per square centimeter to the contents of the para sample bulb and 4.4×10^{13} neutrons per square centimeter to the normal sample bulb, which correspond to an integrated beam current of 3.41×10^{-2} coulomb and distances of 5.2 and 6.7 centimeters, respectively, between the target and the para and the normal sample bulb centers.

To obtain the energy dose corresponding to these fluxes, values of neutron cross section from reference 7 and values of neutron flux from reference 5 were used in a first-collision calculation. The effective average neutron energy was found to be 10 MeV. The calculated energy deposited for unit integrated flux was thus 5.8 MeV per mole per neutron per square centimeter. From these values and a total irradiation time of 4.71×10^3 seconds, the neutron induced heating rates are 3.08×10^{-3} and 2.00×10^{-3} calorie per mole per second (cal/(mole)(sec)) in the para and normal samples, respectively.

RESULTS AND DISCUSSION

Figures 2(a) and (b) give the measured vapor pressures of the para and normal liquid-hydrogen samples as a function of time after condensation of the normal sample. For comparison, the change in vapor pressure that would be caused by a 0.01^O K temperature change is shown. Also indicated in these figures are the times when the deuteron beam was on. Figure 2(c) is a similar plot of the difference (para bulb minus normal bulb) of the two vapor pressures.

Examination of the data of figure 2 confirmed an observation made at the time the irradiation was performed, namely, that upon turning on the deuteron beam for the first time (at 5.5 hr) a significant pressure decrease was observed and that thereafter the

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(a) Time variation of para-hydrogen sample vapor pressure.

(b) Time variation of normal-hydrogen sample vapor pressure.

(c) Time variation of vapor pressure difference between hydrogen samples.
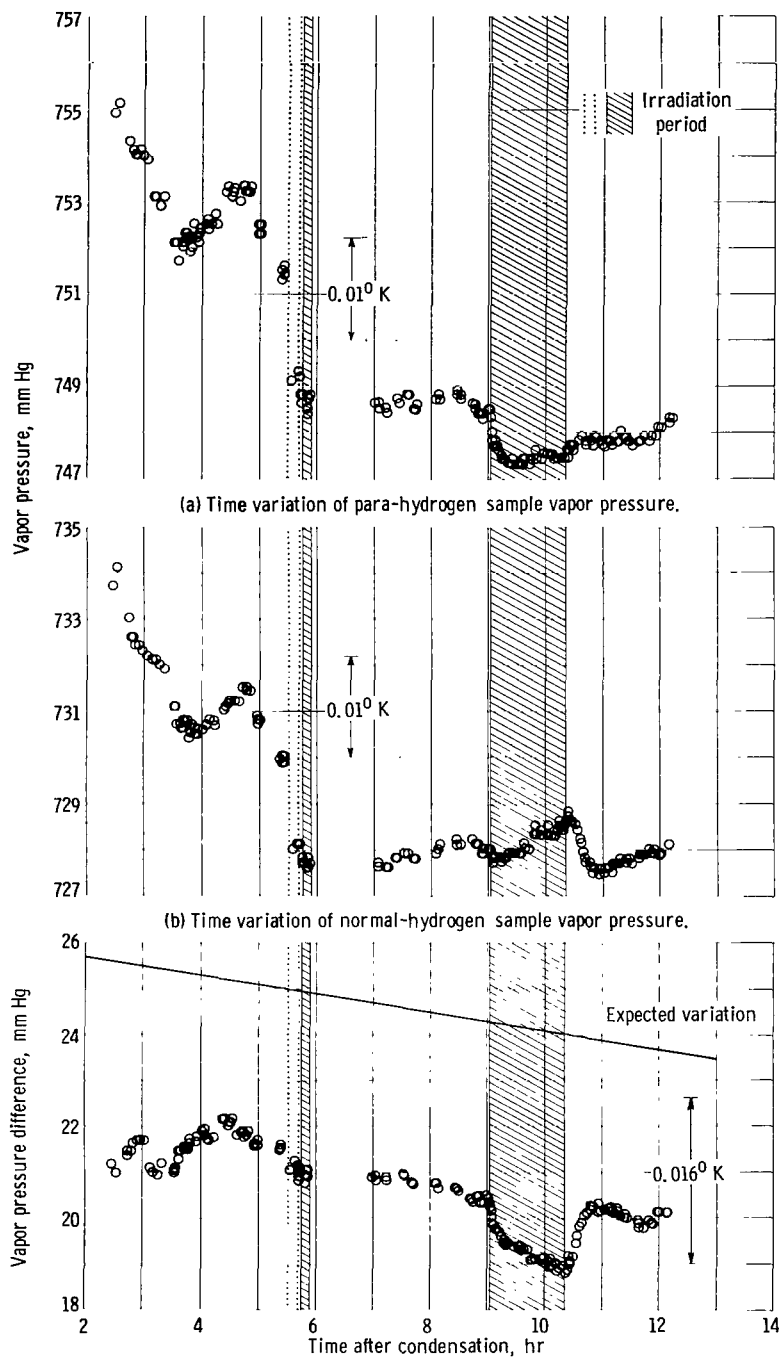
Figure 2. - Radiation effects on liquid ortho- and para-hydrogen.

pressure readings became more stable. This stability was particularly evident during the long irradiation beginning at 9 hours. From these results and observations, it is concluded that (1) the hydrogen bath was superheated to an appreciable extent, (2) convection currents of superheated fluid caused significant temperature fluctuations at the sample bulbs (even though copper screens were employed), and (3) this superheat was largely destroyed by bubble formation centers produced by the neutron irradiation and by the radioactivities induced in the solid parts of the apparatus.

A second prominent feature of the data in figure 2(c) is that the observed pressure differences do not agree with the expected pressure differences. The expected pressure difference, indicated by the continuous curve in figure 2(c), decreases gradually because of spontaneous conversion from an initial value of 26.1 mm Hg. The observed differences between the data points and this curve have two possible explanations: (1) The hydrogen samples are not really of normal and/or equilibrium composition; or (2) the two sample bulbs were not effectively at the same temperature, that is, the normal bulb was slightly warmer than the para bulb.

Although a careful determination of the sample compositions was not performed at the time of irradiation, subsequent to that time tests with a gas conductivity apparatus have been performed. A comparison of the hydrogen from the high-pressure tank and hydrogen from an analytic reagent grade tank indicates that the normal-hydrogen sample was actually 75 percent ortho-hydrogen. Similarly, a sample of gas obtained in exactly the same way as the para sample prior to irradiation was compared with gas that had been completely converted to the equilibrium composition by means of an iron hydroxide catalyst at 20° K (ref. 8). This test indicated an ortho content of only 0.6 percent, which compares favorably with the assumed equilibrium value of 0.21 percent. Since the difference between the observed and the expected vapor-pressure differences of figure 2(c) would require an error in composition of the order of 10 mole percent (see fig. 4, p. 13), we conclude that composition errors are not to blame and that the second suggestion (that the two sample bulbs were not at the same temperature) is the cause of these differences.

The most likely way that the normal-hydrogen sample bulb could have maintained a higher temperature than the para bulb is by internal heating due to spontaneous conversion. With a value of 340 calories per mole as the heat of conversion of ortho-hydrogen to para-hydrogen and an initial conversion rate of 0.0043 per hour (see appendix A), the spontaneous conversion heating rate is calculated to be

$$\left(\frac{dQ}{dt}\right)_{t=0} = 4.03 \times 10^{-4} \text{ cal/(mole)(sec)}$$

(All symbols are defined in appendix B.) Since each sample bulb held about 2 cubic centimeters (0.07 mole) of liquid hydrogen, the total heating rate in the normal bulb amounts
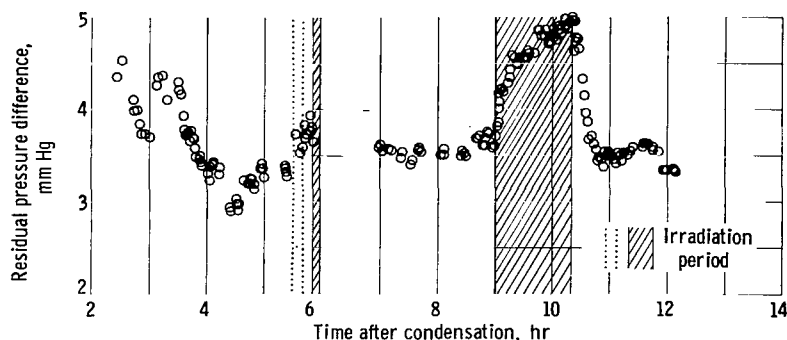
Figure 3. - Time variation of difference between observed and expected vapor pressure differences of liquid ortho- and para-hydrogen samples at normal boiling point of equilibrium hydrogen.

to only about 2.8×10^{-5} calorie per second. At first glance it would seem that such a small heating rate could not account for the observed residual pressures. As is indicated in figure 2(c), however, the observed discrepancy of about 3.5 mm Hg is equivalent to a temperature difference between the samples of only 0.016° K. This temperature difference is of the order of that expected for the stated heating rate when the low conductivities of glass and liquid hydrogen (both about 3×10^{-4} cal/(cm)($^{\circ}$K)(sec)) are taken into account. Therefore, the differences of figure 2(c) are due to an effective temperature difference between the two sample bulbs, amounting to about 0.016° K, which is caused by the heat released in spontaneous conversion.

Since, during the time of the experiment, the composition of the normal hydrogen sample changed because of spontaneous conversion by only about 5 percent, the spontaneous conversion rate remained nearly constant during this time (see eq. (A6) of appendix A). Therefore, the "residue" between the observed and the expected vapor-pressure differences of figure 2(c) is expected to remain nearly constant in time prior to the irradiation. This residue was calculated after the pressure-difference data were corrected for the fact that the samples were not quite at the normal boiling temperature of para-hydrogen. (This correction, which amounted to only about 0.1 mm Hg is discussed in appendix A.) The resulting residual pressure differences are plotted in figure 3.

Prior to the first short irradiations at about 5.5 hours, the results in figure 3 reflect the temperature fluctuations discussed in relation to figures 2(a) and (b); the average value during this time was between 3.5 and 4 mm Hg as expected from these considerations. Between 7 and 9 hours, the data are much more stable and show only a slight decrease up to the time when the irradiation at 9 hours began. During the 78 minutes of the irradiation, a "pressure pulse" is clearly seen. If the residual pressure difference is assumed proportional to the relative heating rates of the two sample bulbs, the pressure pulse (a rise of approximately 1.4 mm Hg) can be equated to an excess heating rate of 1.6×10^{-4} cal/(mole)(sec) just as the residual pressure difference of 3.5 mm Hg

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was related to the spontaneous conversion heating rate of 4×10^{-4} cal/(mole)(sec).

The evidence that heating in the normal sample increases more than in the para sample during irradiation is surprising in view of the fact that the neutron flux in the para bulb is half again as great as that in the normal bulb. Therefore, this heating must be due in part to an exoergic reaction caused directly by the radiation or by some radiation-produced species. Since the only source of energy for the reaction is the rotational energy of the ortho-hydrogen molecule, the reaction must be conversion of ortho- to para-hydrogen.

To obtain the actual heating rate due to radiation-induced conversion, the differential neutron heating must be included. Because the fraction of the energy absorbed from the neutron radiation which appears as heat is unknown, two cases will be considered: Case I in which no heating occurs, and Case II in which all the energy deposited by the radiation appears as heat. The following table summarizes the calculations for these cases:

	Case I	Case II
Differential radiation heating, cal/(mole)(sec)	0.0	[a]10.8×10^{-4}
Apparent heating in pulse, cal/(mole)(sec)	1.6×10^{-4}	1.6×10^{-4}
Induced conversion heating, cal/(mole)(sec)	1.6×10^{-4}	12.4×10^{-4}
Expected increase in residual pressure difference after irradiation, mm Hg	0.1	0.78

[a]See p. 6.

Examination of figure 3 shows that the increase in residual pressure after irradiation was no more than 0.25 mm Hg. Therefore less heating of the hydrogen occurred than was assumed in Case II (see table). Although the pressure pulse is evidence that radiation induced conversion has occurred, we must conclude that less than 5×10^{-3} fractional change in ortho composition was produced by the integrated neutron flux of 5×10^{13} neutrons per square centimeter.

A detailed examination of the data constituting figure 3 revealed that the pressure pulse persisted at a constant value for 4 minutes after the deuteron beam was turned off at 10.3 hours. This persistence was followed by an exponential-like decrease to 3.5 mm Hg with a time constant of about 10 minutes. These times, when contrasted with the 2-minute time constant one would expect from a consideration of the heat capacity of liquid hydrogen, indicate that induced conversion in this experiment is produced by a species which has a precurser with a lifetime of the order of minutes. The relatively long times involved rule out the possibility that this precurser is a primary ion.

From the rate at which energy is deposited by the incident neutrons, the primary ion production rate was calculated by assuming 35 electron volts were required to produce one ion pair. Then, together with the measured recombination coefficient of primary ions in liquid hydrogen (ref. 9), the time for the ion density to decrease to half its value upon termination of the irradiation could be obtained from this production rate. This time was determined to be of the order of 1 millisecond, a time short enough to exclude the possibility that the long-lived precurser was one of the primary ions (H_2^+ and electrons).

CONCLUSIONS

From the experimental observations obtained in this investigation of the effects of fast-neutron radiation on liquid ortho- and para-hydrogen, it is concluded that

1. Radiation-induced conversion of ortho- to para-hydrogen had occurred.

2. The conversion produced amounted to less than 5×10^{-3} fractional change in ortho-hydrogen composition in normal hydrogen for an integrated flux of fast neutrons (10 MeV average energy) of 5×10^{13} neutrons per square centimeter.

3. Conversion was produced by an atomic or molecular species which appeared to have a long-lived (of the order of 5 min) precurser.

4. This long-lived precurser is not one of the primary ionization products (H_2^+ or electrons).

5. The irradiation caused a pronounced reduction in the superheat of the liquid-hydrogen bath.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, November 16, 1964.

APPENDIX A

TREATMENT OF EXPERIMENTAL VAPOR-PRESSURE DATA

The basic data used to determine the molar concentration X of ortho-hydrogen in a liquid-hydrogen mixture are given in figure 18 of reference 10. In that figure, values of the vapor-pressure difference between liquid and equilibrium mixtures of ΔP are given as a function of equilibrium hydrogen pressure for five values of X. Table I lists selected values from reference 10 obtained by careful reading of figure 18. The five values of vapor-pressure difference at the normal boiling points of equilibrium hydrogen ΔP_0 in this table were used to construct the differential

$$\frac{d(\Delta P_0)}{dX} = \alpha + \beta X \tag{A1}$$

where α and β are constants. A reasonable fit of the data was obtained for $\alpha = 17.4$ and $\beta = 46.4$. Integration of equation (A1) with these values yields

$$\Delta P_0(X) = 17.4X + 23.2X^2 \tag{A2}$$

a graph of which is given in figure 4.

TABLE I. - VAPOR-PRESSURE DIFFERENCES

FOR LIQUID ORTHO- PARA-HYDROGEN

MIXTURES (REF. 10)

Pressure of equilibrium mixture, P_E, mm Hg	Mole fraction of ortho-hydrogen, X				
	0.75	0.66	0.57	0.38	0.19
	Vapor-pressure difference, ΔP, mm Hg				
800	27.15	22.35	18.20	10.50	4.35
760	26.10	21.50	17.35	10.05	4.15
700	24.60	20.20	16.30	9.45	3.85
600	21.90	17.95	14.40	8.45	3.40
500	19.20	15.65	12.65	7.35	2.95
400	16.00	13.35	10.65	6.10	2.45
300	12.80	10.50	8.40	4.90	1.95
200	9.35	7.65	6.15	3.55	1.35
100	5.35	4.35	3.60	2.00	.75

Further examination of the data in the table revealed that in the neighborhood of the normal boiling point, the data were fit reasonably well by the relation

$$\frac{\Delta P}{\Delta P_0} = \left(\frac{P_E}{P_{E,0}}\right)^{3/4} \tag{A3}$$

Figure 5 shows a log-log plot of values read from reference 10. Lines with a slope of 3/4 have been drawn in. From equations (A2) and (A3), it is thus possible to measure the concentration of ortho-hydrogen in a liquid sample given the vapor-pressure difference between that sample and a known composition sample at the same temperature.
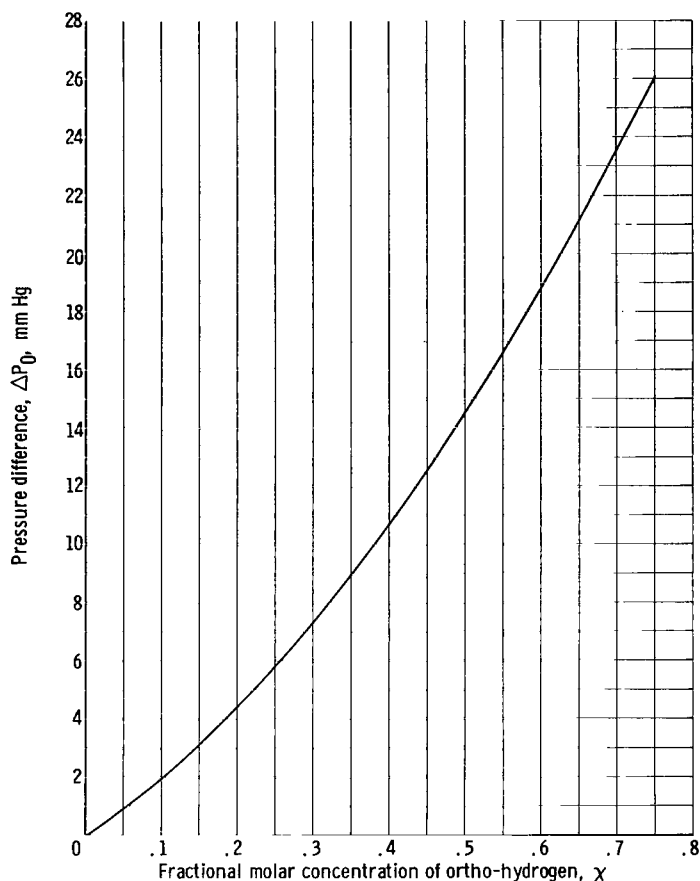
Figure 4. - Vapor-pressure difference of liquid ortho- para-hydrogen mixtures at normal boiling point of equilibrium hydrogen.
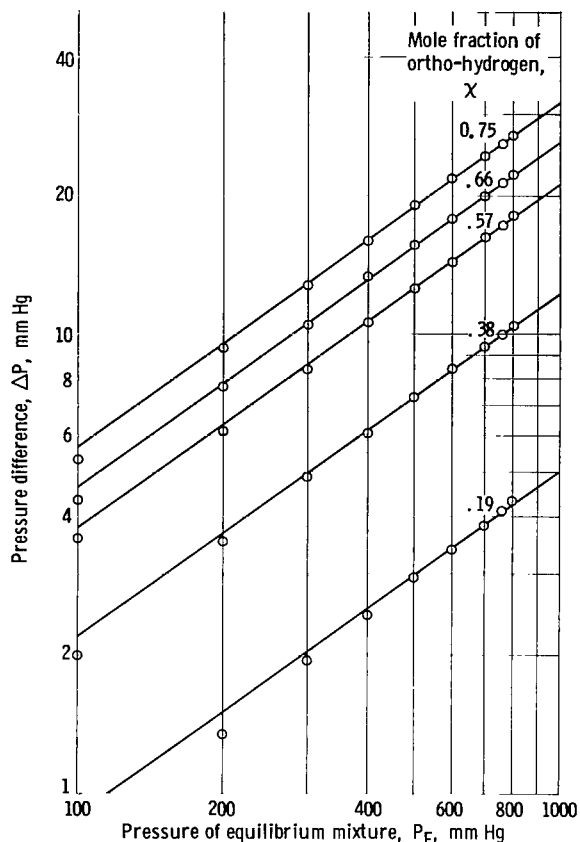

Figure 5. - Vapor-pressure differences of liquid ortho-para-hydrogen mixtures (ref. 10).

A measurement of the rate of change of vapor-pressure difference with time due to spontaneous conversion of ortho- to para-hydrogen is given in reference 6 and is referred to in reference 10. This measurement indicated that, for pure (oxygen-free) normal hydrogen, the rate of change of vapor-pressure difference immediately upon condensation is -0.23 mm Hg/hr at the normal boiling point of normal hydrogen. If this result is converted to the rate of change of vapor-pressure difference at the normal boiling point of equilibrium hydrogen by use of equation (A3)

$$\left[\frac{d(\Delta P_0)}{dt}\right]_{\chi=0.75} = -0.224 \text{ mm Hg/hr} \qquad (A4)$$

Combining this result with equation (A1) and the given values for α and β yields

$$\left(\frac{d\chi}{dt}\right)_{\chi=0.75} = -0.0043/\text{hr} \qquad (A5)$$

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With the assumption that the equilibrium equation may be approximated by

$$-\frac{d\chi}{dt} = k\chi^2 \tag{A6}$$

$k = 0.0076$ per hour per mole. This value does not agree with the equilibrium constant given in reference 6 (and quoted elsewhere), because there it was assumed that liquid mixtures of ortho- and para-hydrogen were ideal solutions, which is equivalent to assuming $\beta = 0$ in equation (A1). Solution of equation (A6) gives

$$\chi = \frac{1}{k(t + \tau)} \tag{A7}$$

where $\tau = 175.4$ hours for $k = 0.0076$ per hour as the time variation of the molar fractional concentration of freshly condensed, pure normal hydrogen.

APPENDIX B

SYMBOLS

k   velocity constant for spontaneous conversion

P   vapor pressure

ΔP vapor-pressure difference between liquid mixture and equilibrium mixture

Q   heat released in conversion of ortho- to para-hydrogen

t   time

α constant in vapor-pressure-difference equation

β constant in vapor-pressure-difference equation

χ mole fraction of ortho-hydrogen in mixture

Subscripts:

E   equilibrium mixture

0   normal boiling point temperature (20.27° K) of equilibrium hydrogen

Superscripts:

o   ortho

p   para

REFERENCES

1. Evans, Robley D.: Principles for the Calculation of Radiation Dose Rates in Space Vehicles. Rep. 63270-05-01, Arthur D. Little, Inc., July 1961.

2. Hehs, W. A., and Miller, G. E.: Measured and Calculated Nuclear Radiation Distributions in Liquid Hydrogen. NASA CR-54003, 1964.

3. Carter, H. G.: Energy Storage Mechanisms in Liquid Hydrogen. NARF 62-15T, General Dynamics Corp., Oct. 31, 1962.

4. Farkas, Adalbert: Orthohydrogen, Parahydrogen, and Heavy Hydrogen. Cambridge Univ. Press, 1935.

5. Tochilin, E., and Kohler, G. D.: Neutron Beam Characteristics from the University of California 60-Inch Cyclotron. USNRDL-TR-129, Naval Radiological Defense Lab., Jan. 9, 1957.

6. Scott, R. B., Brickwedde, F. G., Urey, Harold C., and Wahl, M. H.: The Vapor Pressures and Derived Thermal Properties of Hydrogen and Deuterium. J. Chem. Phys., vol. 2, no. 8, Aug. 1934, pp. 454-464.

7. Hughes, Donald J., and Schwartz, Robert B.: Neutron Cross Sections. BNL-325, Second ed., AEC, July 1, 1958.

8. Weitzel, D. H., Loebenstein, W. V., Draper, J. W., and Park, O. E.: Ortho-Para Catalysis in Liquid Hydrogen Production. J. Res. Natl. Bur. Std., vol. 60, no. 3, Mar. 1958, pp. 221-227.

9. Zessoules, N., Brinkerhoff, J., and Thomas, A.: Recombination and Mobility of Nuclear Radiation Induced Ionization in Liquid Hydrogen. Tracerlab, Inc., Feb. 1962.

10. Woolley, Harold W., Scott, Russell B., and Brickwedde, F. G.: Compilation of Thermal Properties of Hydrogen in Its Various Isotopic and Ortho-Para Modifications. J. Res. Natl. Bur. Std., vol. 41, no. 5, Nov. 1948, pp. 379-475.

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